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EXPERIMENTAL ANALYSIS OF POOL BOILING HEAT TRANSFER USING STAINLESS STEEL

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ABSTRACT

Boiling heat transfer is a critical phenomenon in thermal systems, widely applied in power generation, refrigeration, and chemical processes. Among boiling mechanisms, pool boiling is highly effective for achieving high heat transfer rates. This study investigates the pool boiling heat transfer characteristics of stainless steel 304 (SS304) as a thermos wall material immersed in water, focusing on the critical heat flux (CHF), the maximum heat transfer rate before the onset of film boiling. Film boiling significantly reduces heat transfer efficiency and poses safety risks in industrial systems. SS304 is selected for its superior thermal conductivity, corrosion resistance, and industrial relevance. The study examines the effects of surface properties, heat input, and boiling dynamics on CHF, addressing gaps in experimental data for SS304 in such setups. The experimental system uses a steel vessel with controlled heating, thermocouples for temperature measurement, and real-time data logging. Heat flux on the SS304 thermo wall is gradually increased to measure CHF, with surface temperature, boiling intensity, and heat flux closely monitored. The findings aim to optimize boiling heat transfer systems by providing reliable CHF data for SS304 under pool boiling conditions. This research also lays the groundwork for exploring surface modifications and material improvements to enhance boiling performance, offering insights valuable to energy, manufacturing, and process industries where efficient thermal systems are critical.

KEYWORDS: Pool Boiling, Critical Heat Flux, Stainless Steel 304

1. INTRODUCTION

Pool boiling is extensively used in industrial applications where high heat flux and efficient heat transfer are required, such as in power plants, electronics cooling, desalination systems, and chemical processing. The process involves heat transfer from a heated surface to a liquid, leading to the formation, growth, and detachment of vapor bubbles. The complexity of pool boiling arises from the interplay of thermal, hydrodynamic, and material properties that govern the bubble dynamics and overall heat transfer efficiency. Among the various materials used in pool boiling studies, stainless steel (SS 304) is a preferred choice due to its excellent thermal stability, corrosion resistance, and mechanical strength. The surface characteristics of SS 304 make it suitable for applications in harsh environments, including high-temperature and sub-atmospheric conditions. The study of bubble dynamics on stainless steel rods provides a foundation for optimizing pool boiling systems for practical industrial use. Bubble departure diameter (BDD), bubble departure frequency (BDF), critical heat flux (CHF), and heat transfer coefficients (HTC) are critical parameters in understanding the efficiency of the boiling process. This study aims to fabricate a temperature-controlled pool boiling setup to systematically analyse these parameters, particularly focusing on bubble behaviour and heat transfer characteristics on the SS 304 thermowell.

2. MATERIALS AND METHODS

1. **SS304 Rod:**
   SS304 rod (fig 3.1), measuring 15 cm in length and 20 mm in diameter, serves as a crucial component in your pool boiling project. Stainless Steel 304 is widely chosen for such applications due to its excellent corrosion resistance, mechanical strength, and good thermal conductivity. The rod's geometry and material properties make it suitable for studies on heat transfer and boiling phenomena. In a pool boiling setup, the rod is typically heated to investigate bubble formation, growth, and heat flux characteristics. Its surface can be modified or treated to explore enhancements in boiling performance, providing insights into thermal management and energy efficiency improvements in industrial and scientific contexts.

2. **Thermowell:**
   The setup involves an SS304 rod with a thermowell (fig 3.2) integrated into its core, which is then submerged in water for the pool boiling experiment. The thermowell houses the heating element, ensuring uniform heat distribution along the rod's surface. The SS304 material provides excellent thermal conduction and corrosion resistance, making it suitable for prolonged use in water. This arrangement enables precise control of the rod's temperature, facilitating the study of critical heat flux during the boiling process.

3. **3. Steel vessel :**
   The steel vessel shown is (fig 3.3) an integral part of the pool boiling experimental setup. It is designed to hold water and immerse the SS304 rod equipped with a thermowell. Constructed from durable materials, the vessel ensures resistance to high temperatures and corrosion, making it ideal for prolonged boiling experiments. Its welded joints provide structural integrity, preventing leaks under thermal stress. The vessel's dimensions are likely tailored to optimize the distribution of heat around the rod, ensuring consistent boiling conditions. This setup allows for detailed observation and analysis of boiling behavior, heat flux, and temperature distribution in the water.

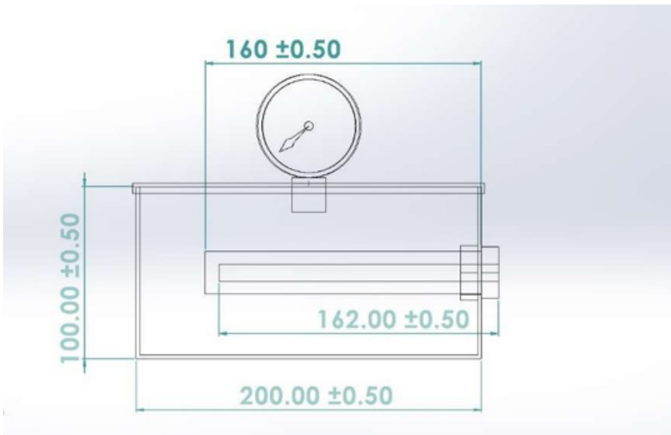
4. **Pressure gauge:**
   The pressure gauge shown (fig 3.4) is installed on top of the vessel used in the pool boiling experiment. Its primary purpose is to monitor the pressure within the system as the water is heated and boiling occurs. This ensures that the experimental conditions remain controlled and within safe operational limits. By providing real-time pressure readings, the gauge aids in analysing the relationship between pressure, temperature, and boiling heat transfer phenomena. It also helps identify critical points such as the onset of nucleate boiling and critical heat flux, essential for accurate data collection and system safety.

5. **Max6675 module:**
   The MAX6675 module (fig3.5) is utilized in the pool boiling project to interface with a Type K thermocouple for accurate temperature measurements. This module converts the analog voltage generated by the thermocouple into a digital signal, which can be read by a microcontroller or data acquisition system. In the pool boiling setup, the thermocouple, connected to the MAX6675, measures the surface temperature of the SS304 rod or the water temperature in the vessel. The MAX6675 ensures precision through its built-in cold-junction compensation and a resolution of 0.25°C, allowing for detailed analysis of heat transfer processes and boiling phenomena. Its compact size and digital SPI interface make it easy to integrate, ensuring reliable temperature monitoring throughout the experiment.

6. **Arduino**
   In the pool boiling project, an Arduino microcontroller (fig 3.6) is used as a central unit for data acquisition and control. It interfaces with the MAX6675 module to read temperature data from the Type K thermocouple and processes the measurements in real time. The Arduino's simplicity and versatility allow it to handle multiple inputs, such as the thermocouple, pressure sensors, or other monitoring devices. The collected data can be displayed on an LCD screen, logged onto an SD card, or transmitted to a computer for analysis. Additionally, the Arduino can be programmed to control the heater's power supply, enabling precise regulation of the rod's temperature. Its open-source platform and compatibility with numerous sensors make it an ideal choice for automating and monitoring critical aspects of the pool boiling experiment.

7. **Digital volt And Ammeter**
   In the pool boiling project, a digital voltmeter and ammeter (fig 3.7) are essential for monitoring the electrical power supplied to the heating element. The digital voltmeter is used to measure the AC voltage (ranging from 90 to 500V) applied to the heater, ensuring that the voltage remains within the desired range for consistent heating performance. The digital ammeter, with a range of 1.0 to 50A AC, monitors the current flowing through the heating element, providing real-time feedback on the electrical power being consumed. By measuring both voltage and current, these instruments allow for precise control of the power input to the heater, helping to maintain a stable and controlled heating environment. This data is crucial for understanding the heat transfer process and for ensuring the safety of the experiment by preventing overheating or power surges that could affect the boiling dynamics or damage the equipment.

8. **Dimmer Stat**
   A dimmer stat (Fig 3.8) in pool boiling experiments is used to control the voltage supplied to the heating element, which regulates the heat flux. By adjusting the voltage, you can observe different boiling behaviours and regimes in the liquid being heated. This helps in studying the dynamics of boiling and heat transfer processes.



1. Vessel size: 200mm*100mm
2. Rod diameter: 25mm
3. Rod length: 160mm

Fabrication: Key fabrication steps included:

1. ***Material Preparation:*** Insertion of cartridge heater into the stainlesssteel rod of diameter 25mm and preparation of pool boiling setup of stainless steel material.
2. ***Component Assembly:*** Assembling components such as an SS304 rod with thermowell, steel vessel, thermocouple, MAX6675 module, Arduino, dimmer stat

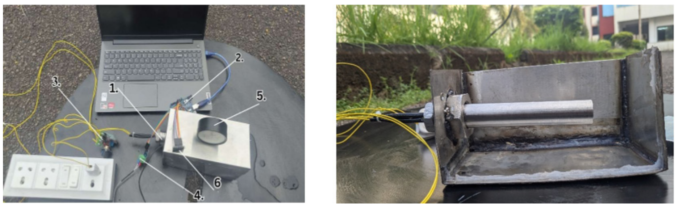


Fig 3 Fabricated components

3. EXPERIMENTATION AND TESTING

The working of the experimental setup for pool boiling follows a systematic approach to study heat transfer characteristics and determine the critical heat flux (CHF) of an SS304 rod. The setup features an SS304 rod (15 cm in length and 20 mm in diameter) equipped with a thermowell housing a cartridge heater for uniform heating. The rod is fully submerged in a steel vessel filled with water, designed to maintain structural integrity under high-temperature conditions. The vessel includes a pressure gauge for real-time monitoring of system pressure. The cartridge heater is powered by an AC power supply, with input voltage (90–500 V) and current (1.0–50 A) continuously monitored using a digital voltmeter and ammeter to ensure precise regulation of heat input.

As the heater activates, heat is conducted through the SS304 rod and transferred to the surrounding water. When the surface temperature of the rod exceeds the boiling point of water, vapor bubbles begin to form at nucleation sites, initiating the nucleate boiling regime. This phase is characterized by high heat transfer efficiency due to intense liquidvapor interactions. A thermocouple embedded in the thermowell measures the rod's surface temperature, and the data is processed through the MAX6675 module, which converts the thermoelectric signal into digital readings. These readings are displayed in real-time by an Arduino microcontroller, enabling accurate monitoring of temperature variations throughout the experiment.

As the heat input increases incrementally, the intensity of bubble generation rises. The experiment seeks to identify the critical heat flux (CHF), the maximum heat transfer rate at which the liquid in contact with the surface can still wet it. Beyond this point, the transition to film boiling occurs, wherein a vapor layer forms around the rod, drastically reducing heat transfer efficiency and causing a sharp rise in surface temperature. At CHF, the power input is calculated using the voltage and current data to quantify the system's performance.

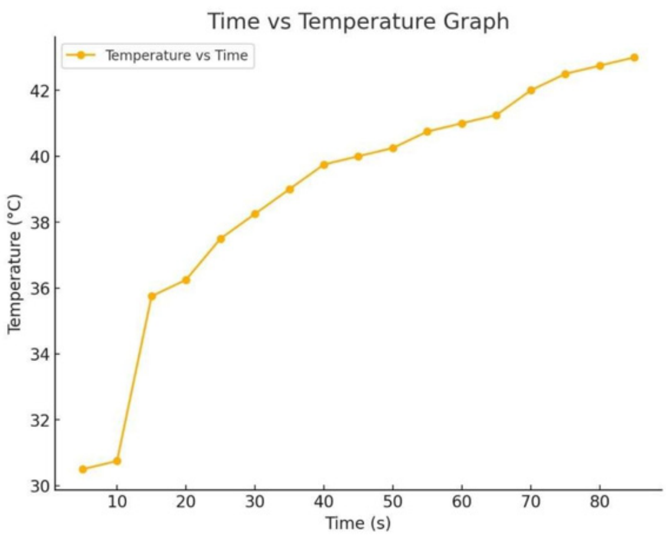
To prevent damage, the experiment is terminated once CHF is observed, and the system is allowed to cool naturally. The data collected—surface temperature, pressure, and power input—is analyzed to compute the heat transfer coefficient and critical heat flux. This refined methodology provides a detailed understanding of the boiling heat transfer process and the thermal performance of SS304 in pool boiling applications.

4. RESULTS AND DISCUSSION

The pool boiling experiment was conducted with readings taken at regular intervals of 5 seconds. The data obtained provided insights into the variation in surface temperature and corresponding heat flux during the different stages of pool boiling. The results are summarized in the table below, which includes the recorded temperatures, heat flux, and time intervals. The boiling curve was plotted using the recorded data, showcasing the relationship between the surface superheat and the heat flux.

Temperature (°C)	Time (s)
30.5	5
30.75	10
35.75	15
36.25	20
37.5	25
38.25	30
39	35
39.75	40
40	45
40.25	50
40.75	55
41	60
41.25	65
42	70
42.5	75
42.75	80
43	85

During the nucleate boiling regime, a significant increase in heat transfer efficiency was observed, characterized by an increase in bubble activity on the heating surface. The experimental results demonstrate the different boiling regimes effectively, highlighting the natural convection, nucleate boiling, and transition regions. The steady rise in surface temperature until the critical heat flux point was evident, after which a decline was observed, indicating the onset of the film boiling regime.



In the pre-boiling phase (80–100 seconds), the temperature rises more steeply from 60°C to 90°C as molecules gain kinetic energy and thermal resistance decreases. Finally, in the boiling transition phase (100–120 seconds), the temperature sharply increases to 100°C, where energy begins contributing to phase change rather than heating. This transition highlights the significance of latent heat in boiling systems.

Key insights include water's high heat capacity, its nonlinear heating behavior, and the balance between heat absorption and loss. These findings inform the design of heat exchangers, boilers, and thermal systems, enhance thermodynamic models, and support energy-efficient heating practices.

5. CONCLUSION

The design and fabrication of the experimental setup successfully created a reliable platform for studying pool boiling phenomena, ensuring precise control and measurement of critical parameters. The evaluation of heat flux in pool boiling revealed that heat flux increases with temperature until the critical heat flux point, after which it stabilizes or decreases based on surface conditions and boiling regimes. The heat flux analysis at different temperatures highlighted the variation in heat transfer across temperature ranges, identifying key thresholds for natural convection, nucleate boiling, and critical heat flux. The study validated theoretical predictions and emphasized the influence of surface properties and fluid behavior on boiling performance. The findings provide valuable insights for optimizing heat transfer processes in industrial applications and designing efficient thermal systems.

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